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DIFFUSION WELDING IN AVIATION TECHNOLOGY

Klodbimierz Karlinski

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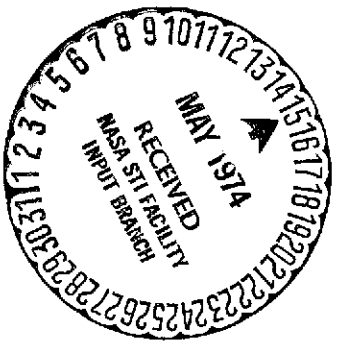

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16. Abstract

Diffusion welding of special heat-resistant alloys for aerospace applications is described in terms of the main process parameters, the required equipment, and the properties of bonds made between various materials. Attention is given to surface cleaning requirements, vacuum and temperature levels used in the process, and the compression of the welded surfaces. Tabulated mechanical properties characterize bonds obtained between steels, heat-resistant alloys, and titanium alloys.

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DIFFUSION WELDING IN AVIATION TECHNOLOGY

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Since the 1950s various countries have developed an interest /25* in diffusion bonding of metal. The method itself is not new: back in 1878, Spring [1] conducted tests of bonding various metals using diffusion bonding and attained great strength in several bonds. This method was later applied repeatedly in the manufacture of samples for research on metal diffusion, but only in the 1950s did they begin to use diffusion bonding as a method of bonding structural elements. The first industrial equipment for diffusion bonding was exhibited at the All-Union Industrial Exhibition in Moscow in 1958.

The growth of diffusion welding technology is closely interwoven with the utilization of new materials in aviation, rocket industry, and nuclear engineering. Welding and soldering of such materials are extremely difficult, considering the tendency toward cleavage and fracture. The cause of these problems is the formation of a fluid phase in the bonding process and the high temperature at which these processes must take place. Consequently, diffusion bonding which is done in the solid state has been found to be efficient, and sometimes the only method for bonding new heat-resistant and special alloy materials.

The Diffusion Bonding Process

The essence of diffusion bonding is the formation of a metallic bond between welded pieces due to the diffusion of atoms across the boundary layers. If diffusion is to occur, the welding surfaces must be physically clean and tight-fitting. The physically clean (removal of oxides, absorbed gases, water vapor,

*Numbers in the margin indicate pagination in the foreign text.

and greasy imputities) surface of the metal will be permanently bonded, if it approximates the distance between the atoms in the crystal lattice. The result is that atoms located on the surface have excess free energy vis-a-vis atoms inside a solid body; and, as we know, this type of structure will be directed to a minimum area, because it corresponds to the minimum of free energy. In reality, the forces of attraction of the metal surface are minimized by their sparseness, which is greater than the interatomic distance. Consequently, the actual surface of contact of the bonded parts is very small. To increase this area during welding, pressure is exerted on the welding surfaces. The quantity of pressure is chosen so that there is plastic flow within the surface's micro-irregularity, which creates conditions favorable to intensive diffusion.

The rate of diffusion depends on many factors, the most important of which is temperature. The coefficient of diffusion which governs this rate is an exponential factor of temperature. To accelerate welding, it is done at high temperatures, at roughly 60-80% of the melting point of the welding metal.

Before welding, the items are degreased and washed; then during welding, heating in a vacuum removes absorbed gases and oxides from the metal surface.

The process of diffusion bonding occurs as follows: after cleaning, the welding pieces are placed in a vacuum chamber. The heat is then turned on and after the proper temperature is attained, pressure is applied. The majority of pure metals are bonded in this manner. In the case of astenitic and heat-resistant steels, this method does not yield satisfactory results, because their surfaces contain oxides whose removal requires the use of space vacuum, and moreover, these alloys are characterized

by a very low rate of diffusion. If these alloys are to be bonded, they must be heated almost to their melting point. Tests have shown that we should introduce a thin layer of some other metal between the bonded surfaces. This metal is diffused to the welding piece and is bonded permanently. During heat treatment of the homogeneous annealing type, there is equalization of the chemical composition through diffusion of the "foreign" metal deep into the welding piece. The removal of oxides from the bond is probably the result of diffusion of oxygen to the metal. /26

Equipment

Standardized equipment for diffusion bonding should be made up of three basic systems: vacuum, heating and compression.

In industrial equipment a vacuum of $10^{-3}10^{-5}$ torr is used, the vacuum system being composed of an input vacuum pump and a diffusion pump. In laboratory devices, compression sometimes reaches 10^{-10} torr, requiring the additional installation of absorption or ion pumps.

The heating system is composed of a heater and feeder. Induction or resistance heaters are generally used. Induction heating is generally used in diffusion bonding of a metal, because it permits attainment of high temperature of the bonding elements in a very short time, without heating of the chamber equipment. Heat shields are unnecessary, which facilitates handling of materials in the chamber and increases its effective capacity. Induction heating is not suited for welding nonconductive materials and semiconductors. Resistance heaters made of molybdenum, tungsten, or tantalum are standard heat sources, because the bonded elements are heated with energy liberated from the heater, whose quantity is not a function of

the type of heated material. A shortcoming of this type of heating is the radiation of energy in all directions, and thus heating of the entire chamber, which destroys the vacuum due to the release of gases from the heated elements and prolongs the cooling period of the welded part.

The type of compression has no effect on the quality of the bond. It may be hydraulic, pneumatic, or mechanical compression.

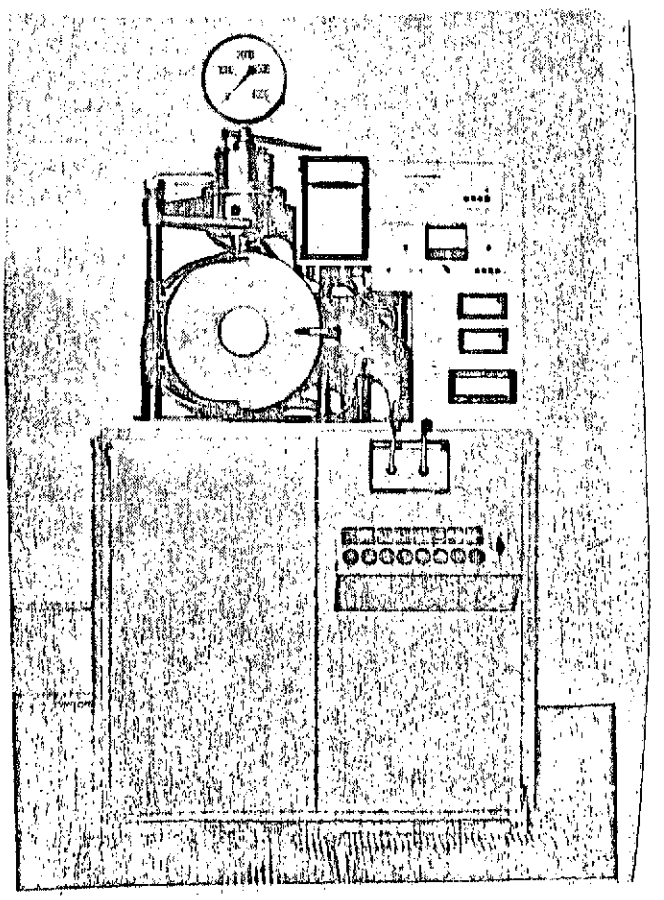

Fig. 1. Device for diffusion bonding, SD-1.

In practice, the type of equipment depends on actual applications. Often we can eliminate the diffusion pump, and instead of compression use the difference in coefficients of linear expansion of the bonding pieces. In the extreme case, welding may be accomplished in a spiral-wound metal or ceramic tube, in an argon atmosphere, where compression is achieved using a helical clamp.

Standard-type equipment was designed and constructed at the Aviation Institute[1] (Fig. 1). The unit is fitted with replaceable resistance heaters of 10 kW output made of tantalum strips. Maximum achieved temperature is a function of the size of

[1] Equipment constructed by E. Kolodziejczyk.

bonding pieces and may be as high as 1600°K for a sample of 20-mm diameter. Maximum size of bonding pieces: diam. 80 x 120 mm. The vacuum pump unit makes it possible to attain vacuums of 10^{-4} torr within 23 minutes after power is turned on, or within 8 minutes if an active vacuum unit is used to evacuate the chamber. A compression unit of the hydraulic type yields maximum compression of 39,000 N (4000 kG). The vacuum chamber, power input of the heater, and compression plunger are water-cooled.

Properties of Diffusion Bonds

In view of the enormous assortment of diffusion-bonded materials, we are limited to citing the bonding properties of materials most widely used in the aviation industry, i.e., acid-proof steels, heat-resistant alloys, and titanium alloys.

Acid-Proof Steels

At the Aviation Institute, tests were conducted on diffusion bonding of Steel 2H13 and Steel 1H18N9T. Bonds welded and soldered with these steels have less strength than that of the original material.

TABLE 1. MECHANICAL PROPERTIES OF BONDING STEELS 1H18N9T AND 2H13.

Type of Material	R_m [MN/m^2] [kG/mm^2]	A_5 [%]	Comments
Steel 2H13	812 (82.8)	20.0	--
Steel 1H18N9T	605 (61.8)	56.8	--
Bonded with interface	602 (62.0)	30.7	Samples cleaved after bonding
Bonded without interface	600 (61.2)	23.2	Two samples cleaved after bonding and two during bonding

Optimum conditions for diffusion bonding: temperature 1073°K, compression 13.7 MN/m^2 (1.4 kG/mm^2), vacuum $2 \cdot 10^{-4}$ torr, heating time at welding temperature 5 minutes. Tests were done on 30-mm diameter samples, whose surfaces had been polished with #400 sandpaper and then etched. Some samples were galvanically nickel-plated to form an interface. The thickness of the nickel layer was 5 micrometers. After bonding, samples were heat-treated, consisting of quenching at 1323°K and tempering at 973°K. Table 1 shows the bonding properties of Steels 1H18N9T and 2H13. Tensile strength of bonding is equal to the strength of Steel 1H18N9T. In Fig. 2 is shown the bonding microstructure after heat-treatment.

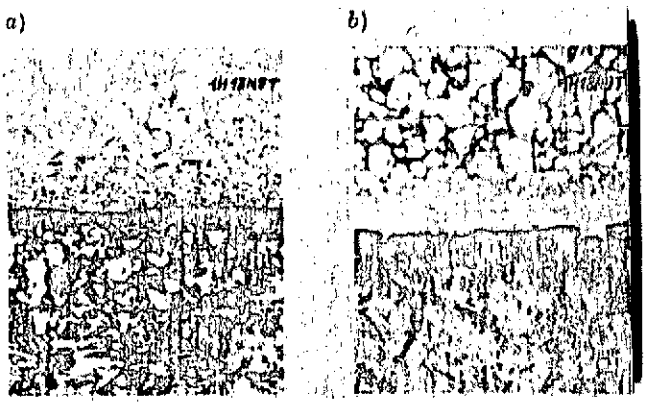

Fig. 2. Microstructure of diffusion bonds of Steels 1H18N9T and 2H13 after heat treatment: a) bond without interface; b) bond with nickel interface.

Heat-Resistant Alloys /27

As a result of our research on diffusion bonding of nickel alloy E1437B, it was found that the vacuum attained by our equipment was insufficient to bond without an interface. An interface of galvanic nickel (10 μm) yielded satisfactory results. Table 2 shows the properties of samples cut from diam. 60 x 10 x 120 mm plugs, diffusion-bonded at 1073°K, with compression at 13.7 MN/m^2 (1.4 kG/mm^2) for 30 minutes. Vacuum was $5 \cdot 10^{-4}$ torr. The plugs were heat-treated, undergoing austeitization at 1355°K for 8 hours and aging at 975°K for 16 hours.[2] For comparison, the properties of the E1437B material and bonded samples are given. Figure 3 shows the bonding micro-

[2]Research on properties of diffusion bonding was done at the People's WSK under the supervision of J. Biedronia.

TABLE 2. MECHANICAL PROPERTIES OF E1437B BONDING.

Type of Material	R_m [MN/m^2] [kG/mm^2]				A_s [%]			
	Temperature °K				Temperature °K			
	293	823	993	1023	293	823	993	1023
Alloy E1437B acc. to [2]	980 (100)	-	735 (75)	-	20	-	15	-
Bonded acc. to [2]	745 (75)	-	658 (67)	-	18	-	18	-
Diffusion-bonded	935 (95.5)	900 (92)	-	748 (76.4)	6.5	8.0	-	5.7

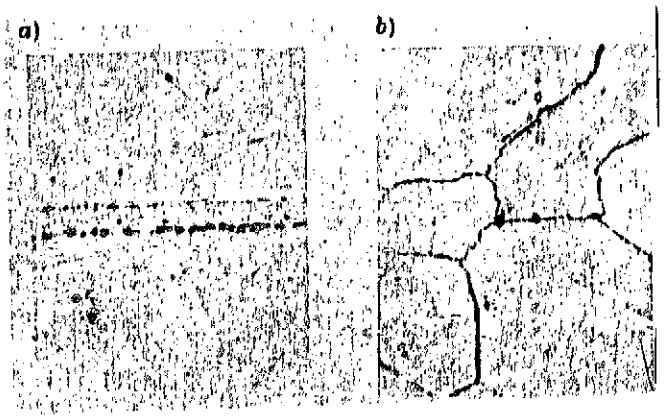

Fig. 3. Microstructure of diffusion bond of E1437B alloy:
a) after bonding, and
b) after heat-treatment.

structure after welding and heat-treatment. As a result of heat-treatment, the nickel layer underwent complete diffusion into the alloy.

In the last 5 years, several publications have appeared on the topic of diffusion bonding of heat-resistant alloys, e.g. [3, 4, 5].

In studies [3] and [5], data are given on bonding of alloys of the Nimonic, Inconel, Incoloy, René-42 and TD-Nickel type; however, in the strength characteristics of bonding, only shearing strength is given, without comparison with the strength of the original metal. Since shearing strength has not been studied for heat-resistant alloys, this data cannot be found in current literature. Consequently, it is impossible to determine the quality of bonding. The authors of study [4] give a description

and results of diffusion bonding of bars of TD-Nickel, which is an agglomerate of nickel with 2% thorium oxide. It is designed for work at temperatures of 1300-1500°K. Bonding of this material is impossible, since in the bond there occurs a deterioration of the hardening effect on the part of the thorium oxide particles. Diffusion bonding at 1366°K for 2 hours with compression at 1.37 MN/m^2 (1.4 kG/mm^2) yields strength of 656 MN/m^2 (67 kG/mm^2) with 22% stretch, and deterioration of samples occurs after bonding. Cobalt alloy was used as the interface.

Titanium Alloys

Bonding of titanium is difficult, considering its great affinity with O_2, N_2 and H_2. These elements reduce ductility and resistance to impact of Ti alloys and increase the tendency of the bonds toward cracking.

Fig. 4. Microstructure of diffusion bond of titanium after bonding [9].

It was found that bonding temperature of Ti [6-9] should not exceed the entectoidal transition point, i.e., 1155°K, since due to violent recrystallization there is a drop in the mechanical properties. Bonding for 7 to 60 min at 1123-1143°K, with compression at 7.35 MN/m^2 (0.75 kG/mm^2) made it possible to attain greater bonding strength than that of titanium (specimens split after bonding) [6]. The properties of the specimen were: Rm = 725 MN/m^2 (74 kG/mm^2), A_5 = 16%. Figure 4 shows microstructure of bond after welding.

Bonding of titanium alloy WT5-1 requires the use of somewhat higher temperature. At 1173-1273°K, with compression at 4.9 MN/m^2 (0.5 kG/mm^2), the bonding process takes 1-5 minutes and

properties are obtained which are equal to the strength and ductility of the alloy. Sample strength was 780-880 MN/m^2 (80-90 kG/mm^2) [7].

Examples of Use

One example of use of diffusion bonding in aerospace technology is radiators (refrigerators) installed in the control system of the Apollo spacecraft [10]. Twenty-five such radiators of chamber type were installed in the control package. The chamber core, made of sheets of aluminum alloy of type 6061, with thickness 2.25 or 4.75, is diffusion-bonded with linings made of alloy 6951, plated with alloy 4045. Figures 5 and 6 show the appearance of manufactured plates and the bonding microstructure. Bonding is done in an air atmosphere at 811-850°K for 74-96 minutes under compression of 2.4 MN/m^2 (0.24 kG/mm^2). Destruction of the sheets during tensile strength tests occurred behind the bonding point. /28

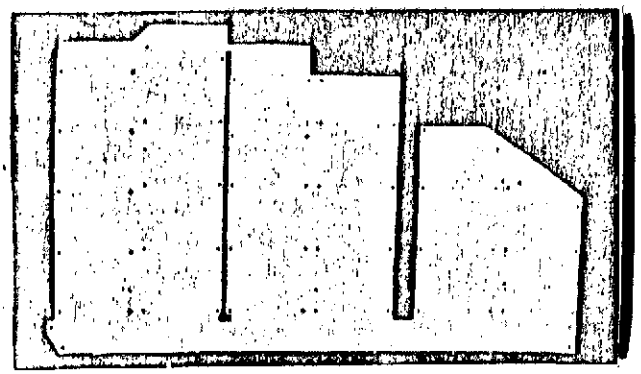

Fig. 5. Radiator manufactured by diffusion bonding of core with aluminum alloy cover sheet (610 x x 1000 mm) [10].

Also designed for spacecraft is the heat shield shown in Fig. 7. It was made from a sheet of TD-NiCr (alloy of nickel containing 20% chromium and 2% thorium oxide) by diffusion bonding [11]. Welding of this material is not recommended for the reasons stated in the description of TD-Nickel. Diffusion bonding was done on a press having 220 kN compression (22.5 tons), in a vacuum of $2 \cdot 10^{-5}$ torr.

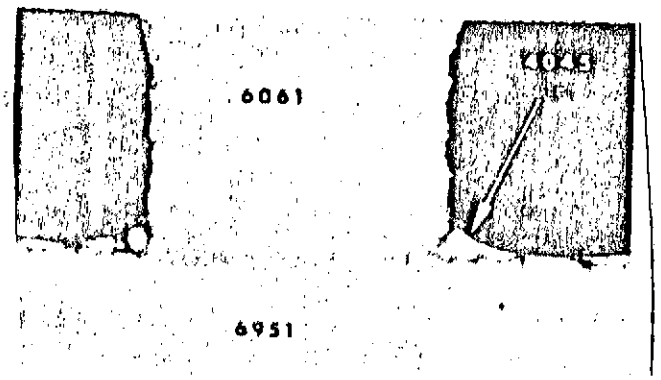

Fig. 6. Diffusion bond microstructure of radiator shown in Fig. 5 [10].

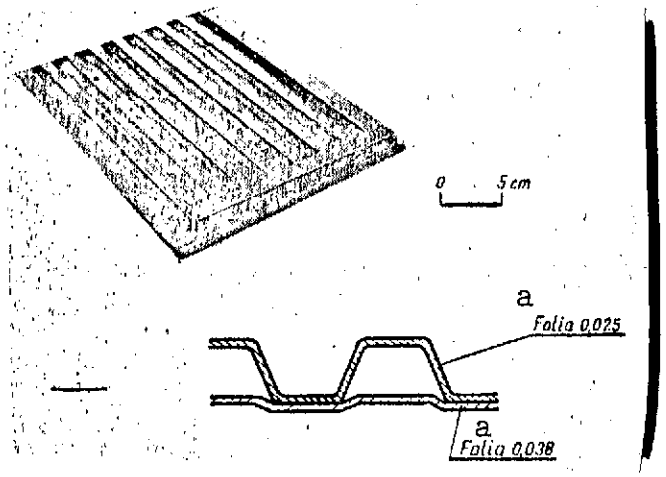

Fig. 7. Heat-shield of TD-NiCr manufactured by diffusion bonding [11].

Key: a. Sheet

Best results were obtained in a two-step bonding process: first at 980°K under 20.7 MN/m^2 compression (2.1 kG/mm^2) for 1 hour; and then at 1463°K under 1.5 MN/m^2 compression (0.15 kG/mm^2) for 2 hours. Sheets made under these conditions are subject to destruction behind the bonding point.

Diffusion bonding may be used not only for joining manufactured pieces, but also to make large forgings [12, 13]. This might be the bonding of several manufactured forgings before the entire assembly is polish-treated, or the joining of several preliminary forging components before further drop-cutting. This is aimed at reducing the consumption of materials and avoiding the need to use large matrices and presses. Figures 8 and 9 show examples of forgings made from titanium alloy type Ti-6Al-4V using diffusion bonding.

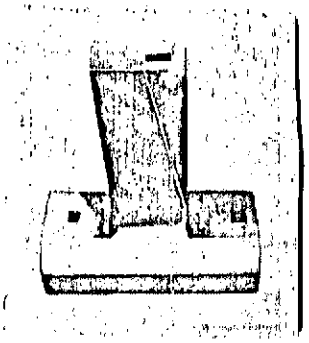

Fig. 8. Element of titanium sheet made by diffusion bonding of octagonal bar 300 x x 400 mm in cross section with bar 82 x 120 mm, 380 mm long and drop-wrought after bonding [13].

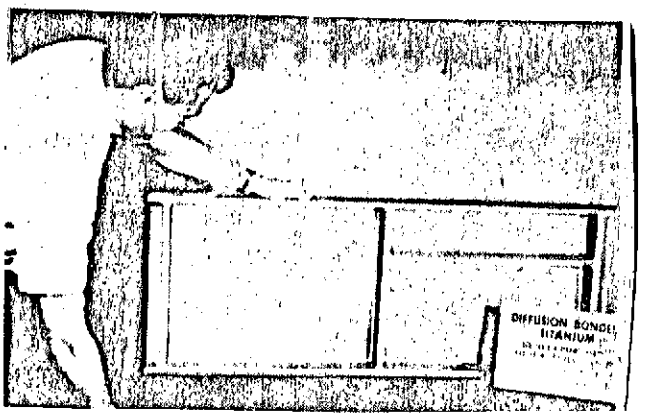

Fig. 9. Element of titanium made from seven forgings, bonded by diffusion bonding process and then drop-wrought.

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*[Note: The author's name and the name of the publishing house have been transliterated from Russian into Polish, and the book title has been translated into Polish.]